Massachusetts Institute of Technology

Idaho National Laboratory

Exelon

Heat Storage for Gen IV Reactors for Variable Electricity from Base-load Reactors

Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems

July 23, 2019: 8:15 am to 5:00 pm (plus dinner)
July 24, 2019: 8:30 to 12:00 Noon

Idaho Falls, Idaho

Role of Heat Storage in Changing Electricity Markets with the Need for Dispatchable Electricity

Charles W. Forsberg
Massachusetts Institute of Technology
Email: cforsber@mit.edu

Electricity Markets are Changing

Addition of Wind and Solar

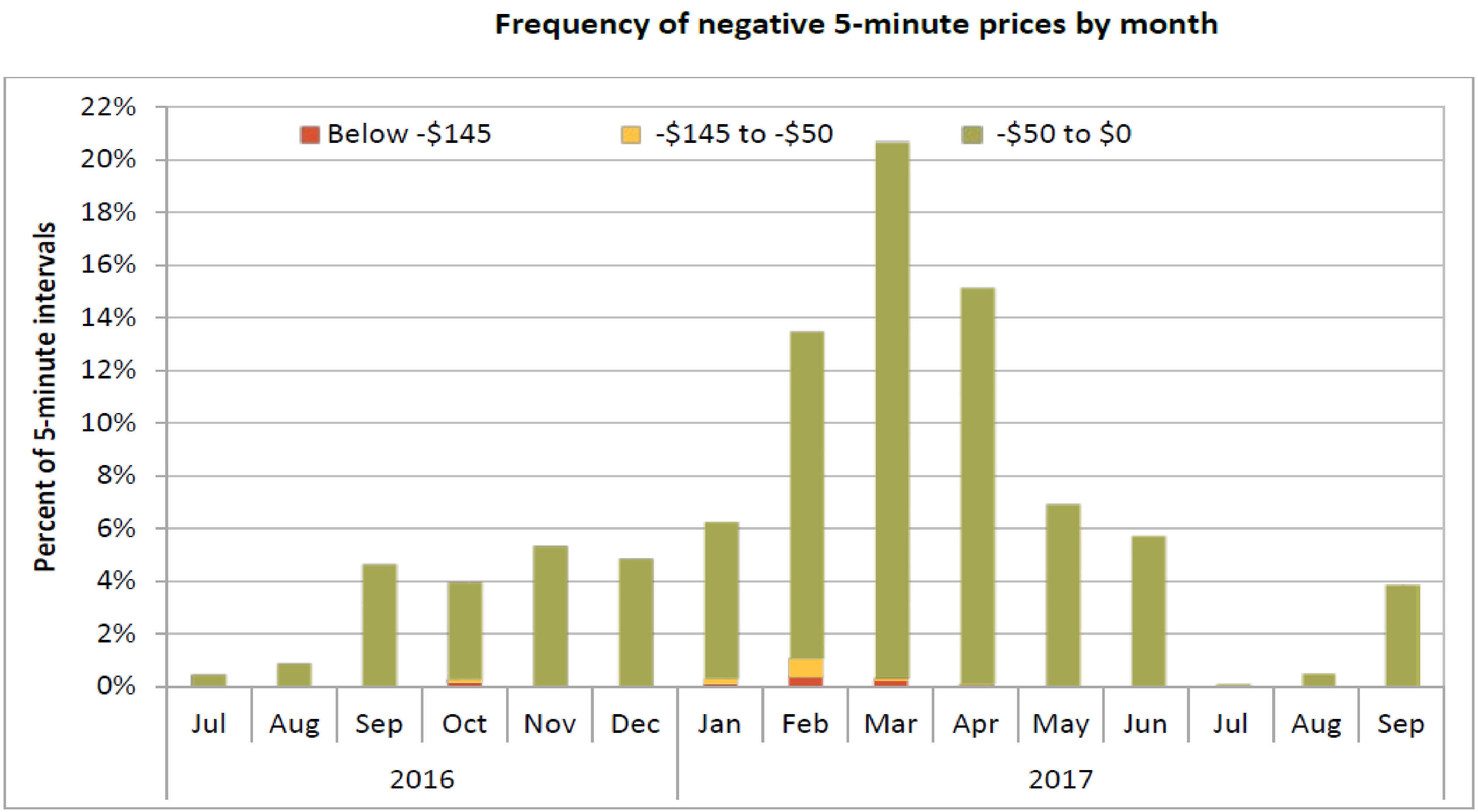
Goal of Low-Carbon Energy System

Large-Scale Solar or Wind Causes Price Collapse and Higher Prices at Other Times

Impact of Added Solar PV on California Wholesale Prices: Value of Wind and Solar Decrease With Scale

Seasonal Mismatch Between Demand and Wind/Solar

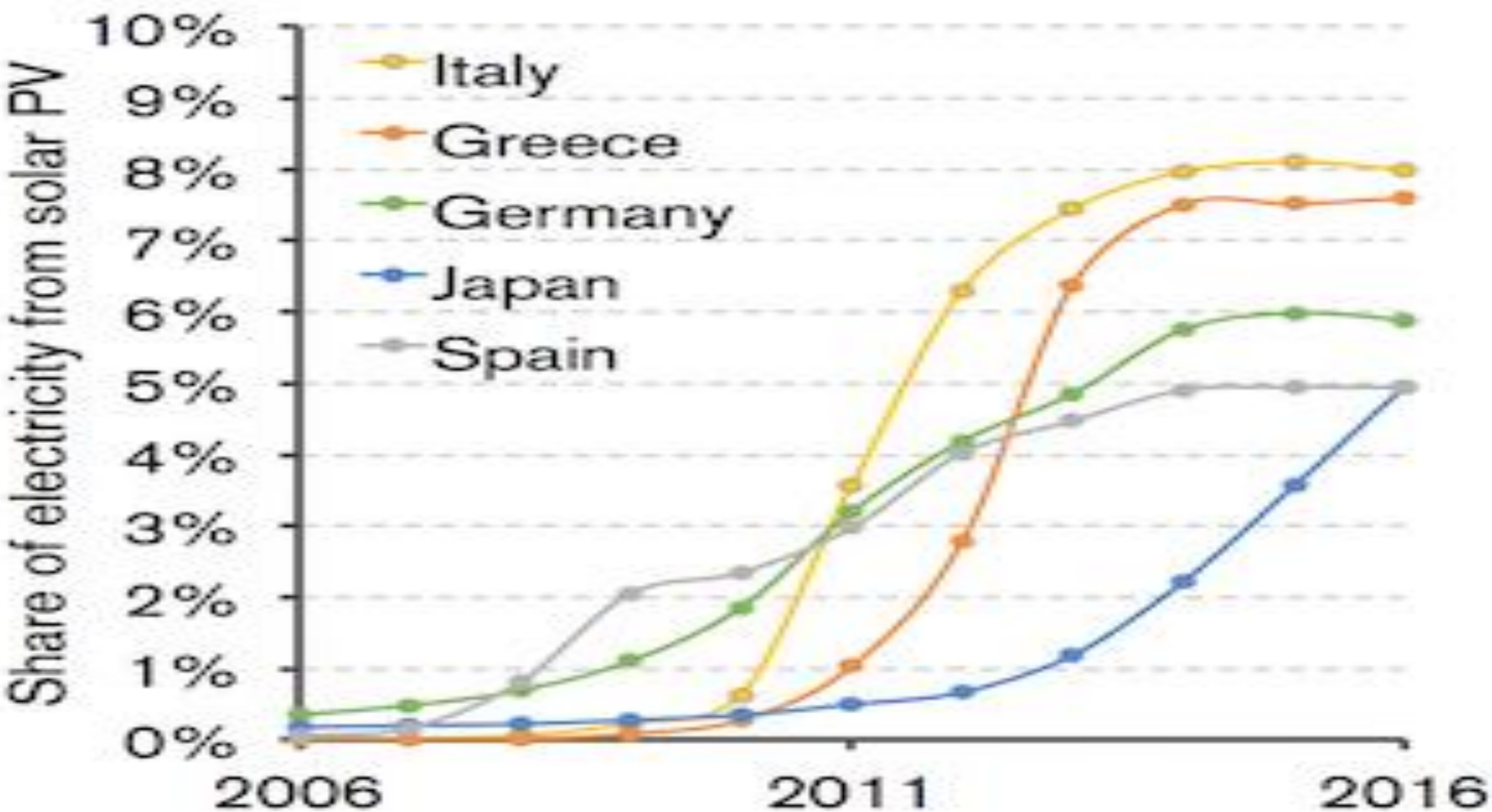
California Negative Wholesale Prices by Month



End of Subsidies and Technology Modifications will Convert Negative-Price to Zero-Price Electricity over Time

Electricity Price (Revenue) Collapse Limits Non-Dispatchable Wind and Solar Without Storage

Saturate Market Even If Large Subsides



Massachusetts Institute of Technology

Varum Sivaram,, "A Tale of Two Technologies", THE BREAKTHROUGH JOURNAL, NO. 8 / WINTER 2018.

Low Levelized-Cost-of-Electricity (Lazard 2017) Does Not Imply Large Market Share

Technology	Energy Form	LCOE: $/MWh(e)	Dispatch	Low-Carbon
Solar PV: Thin Film Utility	Electricity	43–48	No	Yes
Solar Thermal Tower with Storage	Heat	98–181	Yes	Yes
Wind	Electricity	30–60	No	Yes
Natural Gas Peaking	Heat	156–210	Yes	No
Natural Gas Combined Cycle	Heat	42–78	Yes	No
Nuclear	Heat	112–183	Yes	Yes

Dispatchability Is as Important as LCOE

Low-Carbon Energy Sources Have Different Economic Characteristics Than Fossil Fuels

No Change In Energy Policy for 300,000 Years, <u>Throw a Little Carbon on the Fire</u>

Cooking Fire

Natural-Gas Combined Cycle

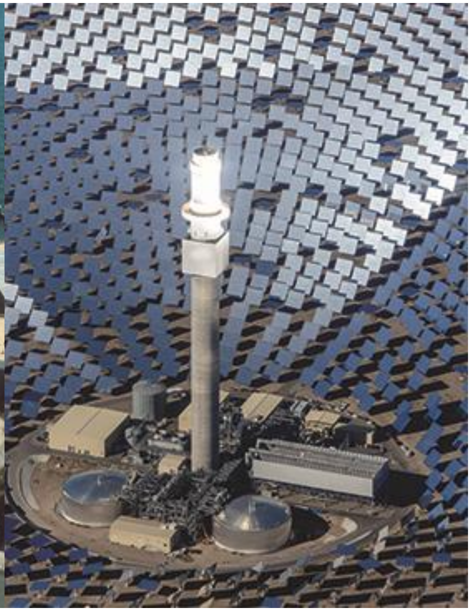
Low-Capital-Cost Power Systems, Labor & Money in Collecting Fuel: Wood or Natural Gas: <u>Economic at Part Load</u>

Fossil Fuels Are Hard to Replace Because They Provide Three Services

- Source of energy
- Low-cost energy storage
- Low-cost dispatchable energy

Low-Carbon System Economics:
High Capital Cost and Low Operating Cost

Operate At Half Capacity Doubles Energy Costs



Produce Electricity **Produce Heat**

Rethinking Energy System Design for Heat Generating Technologies in a Low Carbon World

Nuclear (Fission), Concentrated Solar, Geothermal, Fossil Fuel With Carbon Capture and Fusion (Future)

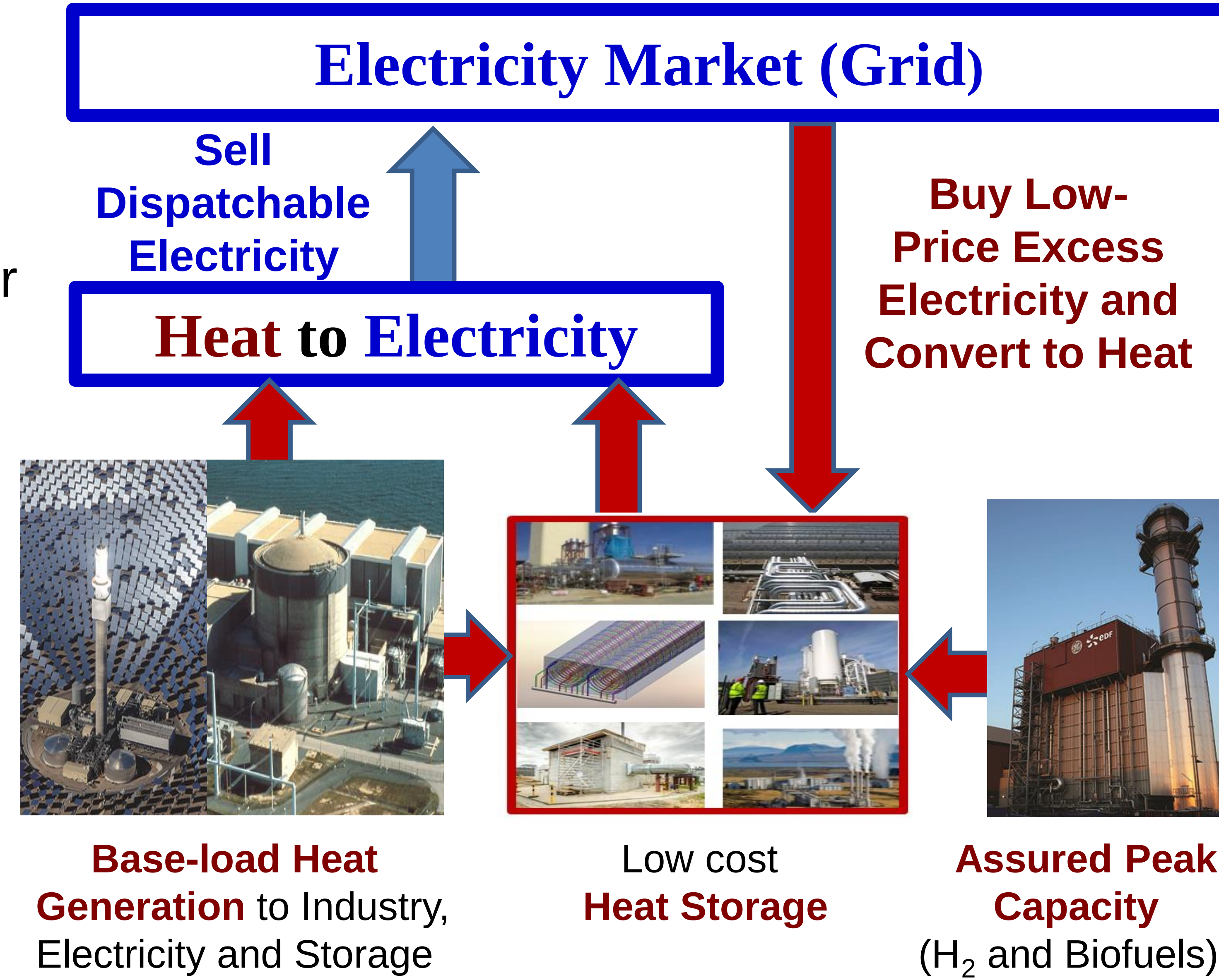
What a Low-Carbon Electricity System Needs

- Sell dispatchable electricity
  - Low cost
  - Assured generating capacity for peak loads
- Buy very-low-price electricity from wind and solar PV at times of excess production: Sets a higher minimum price that improve economics
- Operate nuclear reactors and other heat-generating technologies at base-load to minimize costs

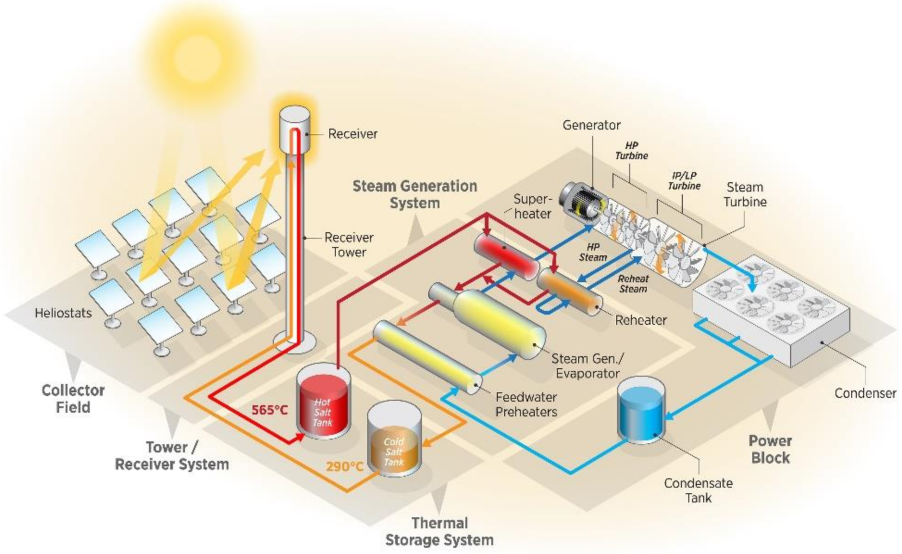
Replace the Storage, Dispatchability and Production Characteristics of Fossil Fuels

Require a New System Design

- Base-load nuclear or CSP
- Heat storage for peak electricity
- Low-price electricity to heat storage
- Backup furnace: assured peak capacity



System Design Applicable to All Heat-Generating Technologies

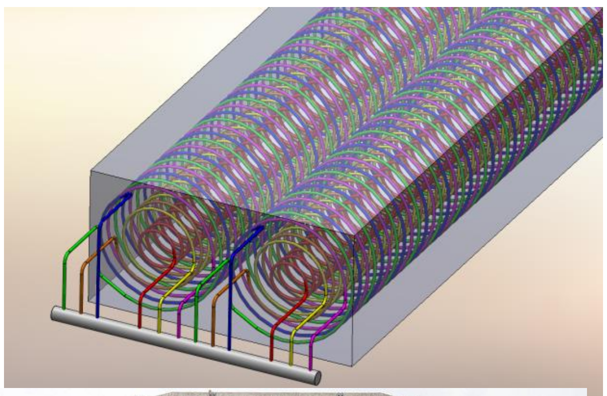


Nuclear Power System | **NREL CSP System**

Low-Cost Heat Storage Couples to Nuclear:
Same Technologies as Concentrated Solar Power

Steam Accumulators

Sensible Heat
(Oil, salt, etc.)



Cryogenic Air

Hot Cement

Geothermal
(Seasonal)

Hot Rock

Heat Storage Is Cheaper than Electricity Storage (Batteries, Pumped Hydro, etc.)

- DOE heat storage goal: $15/kwh(t)
- Battery goal $150/kWh(e), double if include electronics
- **Difference is raw materials cost**

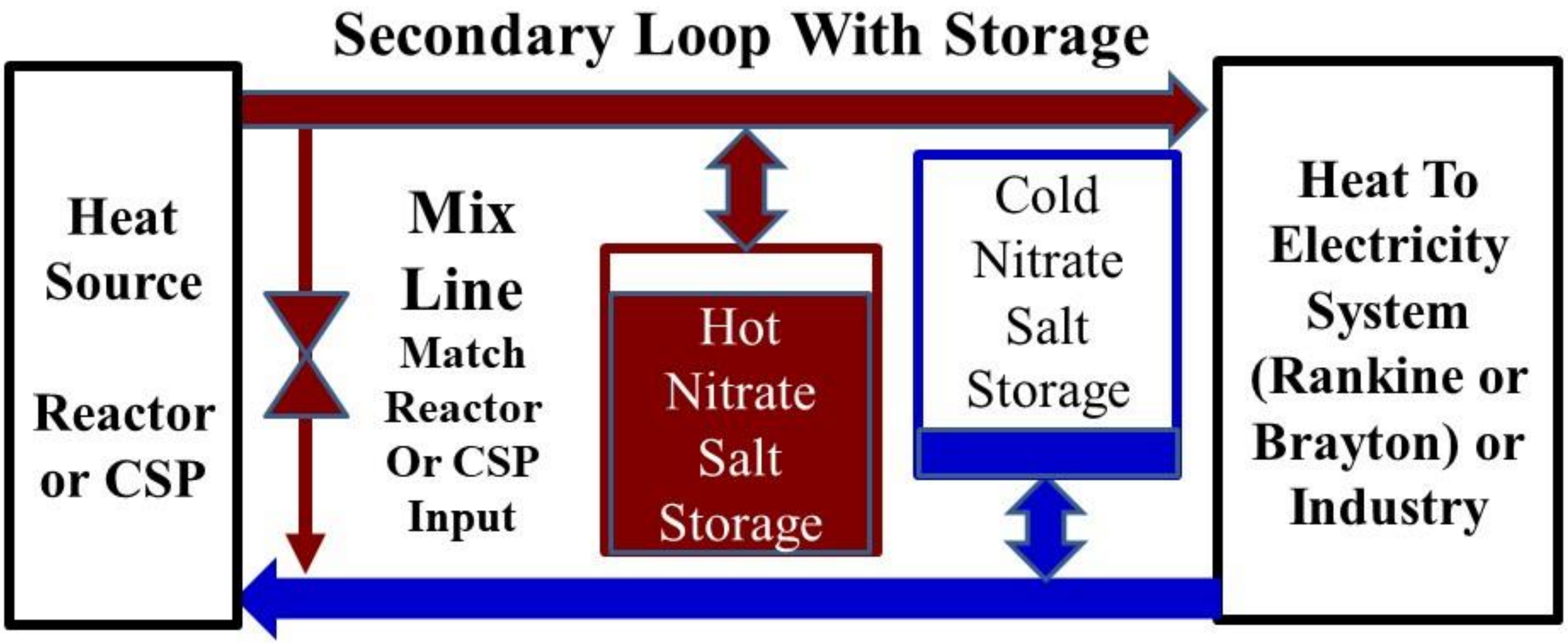
Gigawatt-Hour Heat Storage Technologies	Temperature Limits (°C)
Pressurized Water	<300
Geothermal	<300
Counter Current Sat Steam	<300
Cryogenic Air	<1600
Concrete	>600
Crushed Rock	800
Sand	>1000
Oil	<400
Cast Iron	700/900
Nitrate Salt	<650
Chloride Salt	<1000
Graphite	>1600

Power System Coolant Temperatures Define Allowable Storage Materials

Coolant	Nominal Inlet Temperature (°C)	Nominal Exit Temperature (°C)
NP: Water	270	290
NP: Sodium	450	550
NP: Helium	350	750
NP: Salt	600	700
CSP: Nitrate	290	565
CSP: Chloride	500	725
CSP: Sodium	500	750
CSP: Sand	575	775

Storage Temperature Range Can be Decoupled from Nuclear /CSP System

- Some reactors have small delta T across core
- Large delta T reduce storage costs



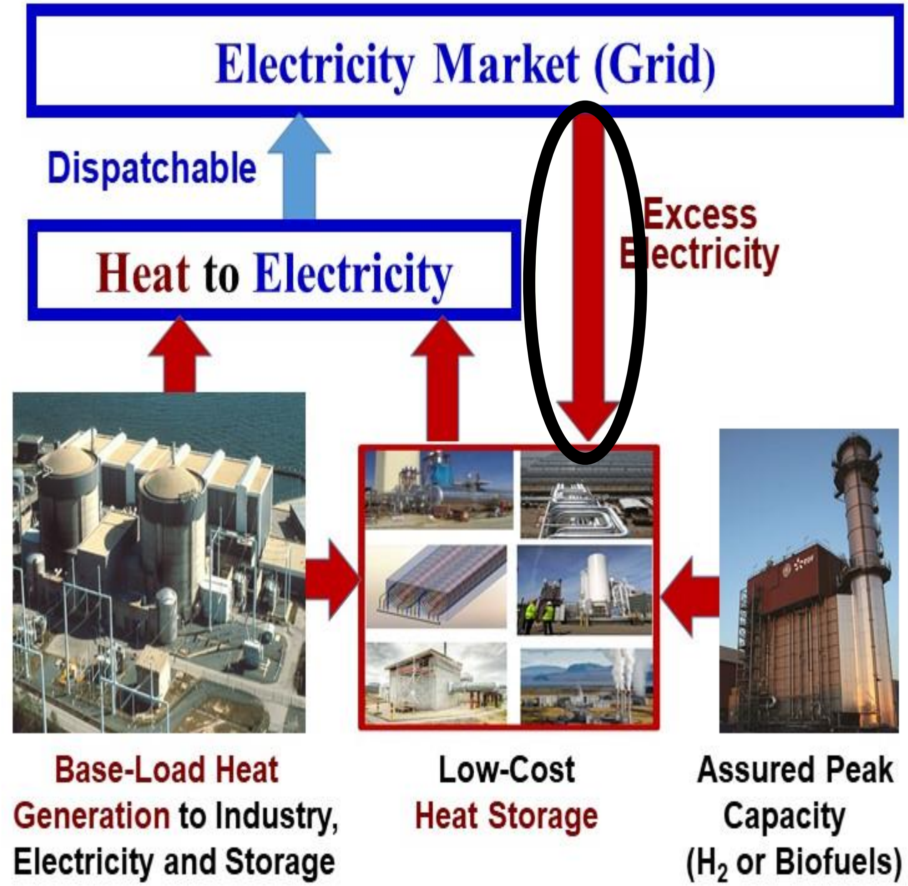
Two Strategies for Peak Power

Heat from Reactor/CSP and Heat Storage

- Oversize Main Turbo-Generator
  - Fast response from operating turbine
  - Peak power capacity limited
  - Turbine efficiency highest at only one power level
  - Low-cost option
- Separate Peaking Turbo-Generator
  - Peaking turbine can be sized to any market
  - Return condenser water to main turbine

If Heat Storage, Buy Low-Price Electricity and Convert to Heat for Later Use

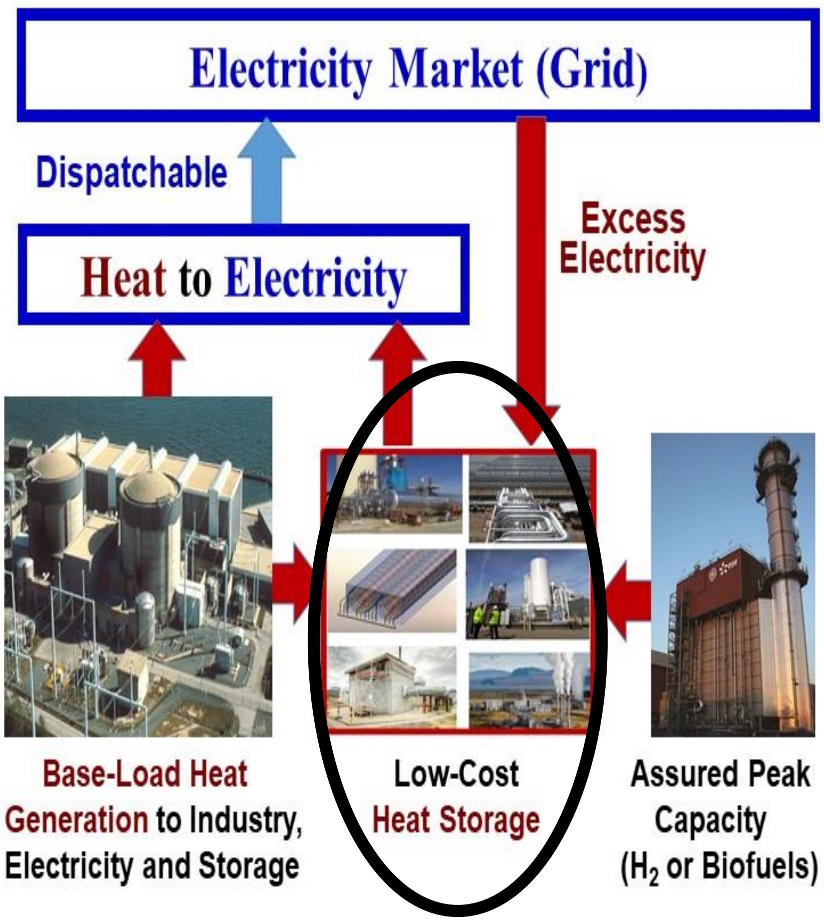
- When low-prices
  - Nuclear generator and grid electricity to heat storage
  - Electric resistance heaters
- Low-cost storage option
  - Same equipment (grid connections, transformers, switchgear) to buy and sell electricity
  - Own storage system and electricity peaking capability
  - Incremental addition to heat storage capacity



Improves Nuclear, Wind and Solar Economics

This System Can Address the Weekday-Weekend Market Challenge

- Low-carbon systems will have excess low-price electricity on weekends: low electricity demand
- Only added cost for weekend-to-weekday storage is incrementally larger heat storage: very low cost



If Heat Storage, Option to Buy Steam Generator for Assured Peak Power

- All storage devices can become depleted but need for assured peak power
- Burns (1) natural gas or (2) low-carbon biofuels and hydrogen
- Low-cost option
  - Use storage electricity peaking capability (turbine generator)
  - Half to third the cost of backup gas turbine for assured capacity

Seldom Used & Low-Carbon Fuel Options

Can Nuclear with Heat Storage Compete with Natural-Gas Peaking Plants?

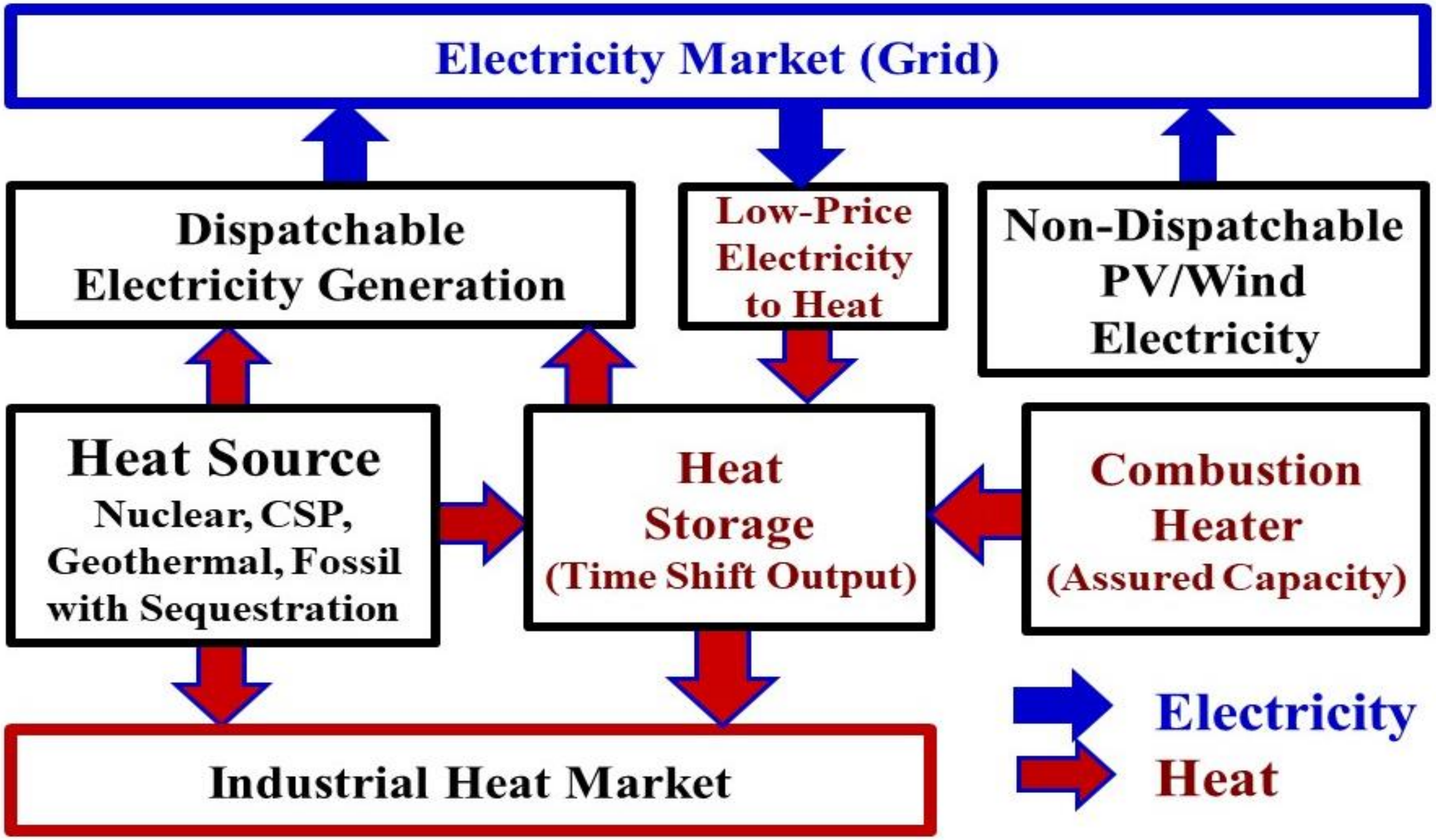
Technology	Energy Form	LCOE: $/MWh(e)	Dispatch	Low-Carbon
Natural Gas Peaking	Heat	156–210	Yes	No
Natural Gas Combined Cycle	Heat	42–78	Yes	No
Nuclear	Heat	112–183	Yes	Yes

- Natural gas peaking plants expensive: High maintenance cost with very high temperature machine plus low capacity factor
- Nuclear with heat storage to replace peaking gas turbine
  - Sell peak power—same as NG peaking plant
  - Assured peak generating capability—same as NG peaking plant
  - Buy low-price electricity for heat storage and peak power—Added revenue

Conclusions

- Electricity market is changing: Volatile prices
  - Deployment of non-dispatchable wind and solar PV
  - Goals of low-carbon economy
- Low-carbon world requires a replacement for fossil fuels as (1) Energy source, (2) Storable energy and (3) Dispatchable energy
- **Require heat storage on the gigawatt-hour scale**
  - **No market 5 years ago, market rapidly growing**
  - **Same challenges for all heat generating technologies**
  - **Enabling technology for economic larger-scale use of nuclear, wind and solar**

Questions



Massachusetts Institute of Technology

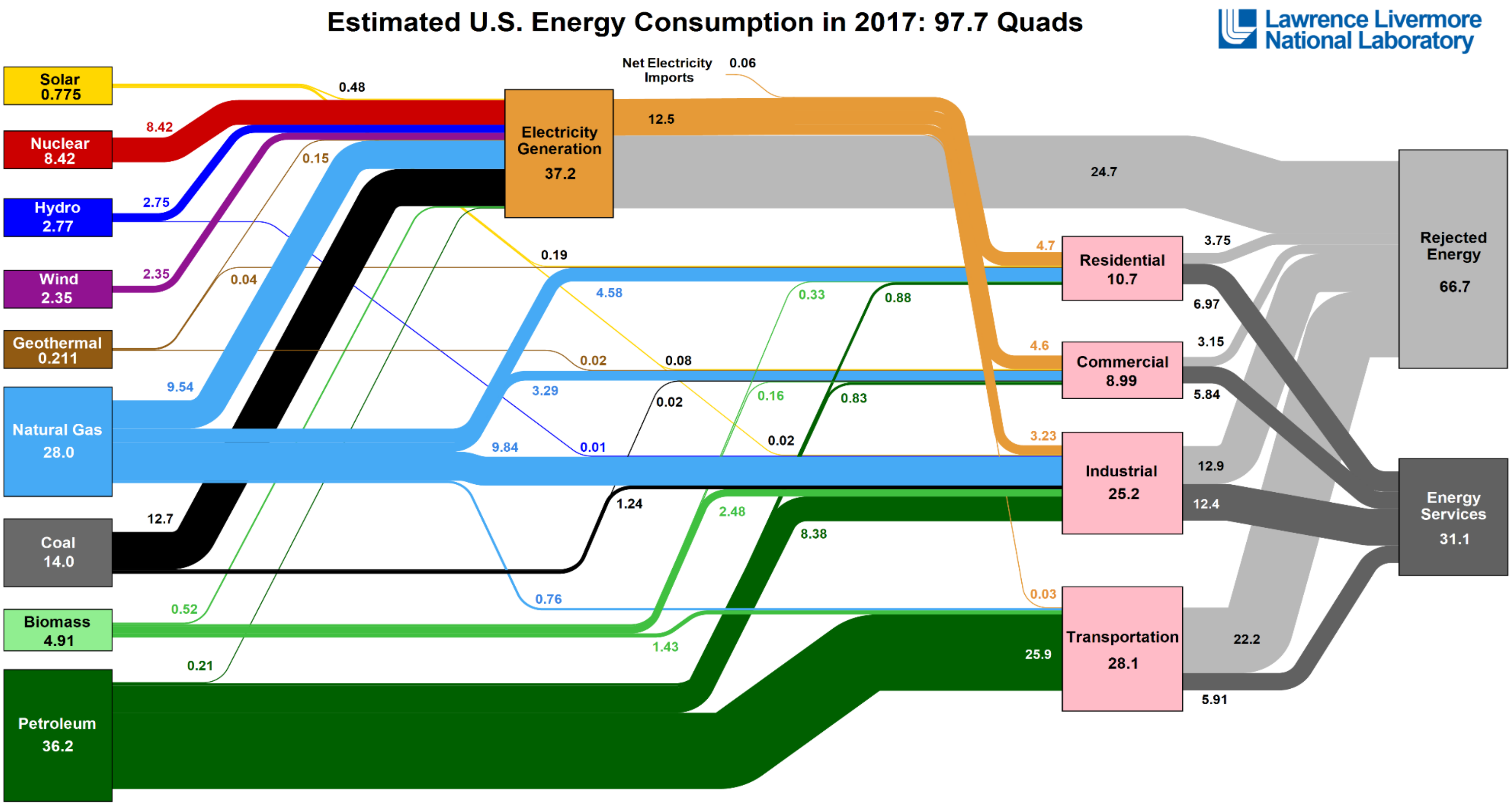
References

1. C. W. Forsberg, “Variable and Assured Peak Electricity from Base-Load Light-Water Reactors with Heat Storage and Auxiliary Combustible Fuels”, *Nuclear Technology* March 2019. https://doi.org/10.1080/00295450.2018.1518555
2. C. Forsberg and P. Sabharwall, *Heat Storage Options for Sodium, Salt and Helium Cooled Reactors to Enable Variable Electricity to the Grid and Heat to Industry with Base-Load Operations*, ANP-TR-181, Center for Advanced Nuclear Energy, Massachusetts Institute of Technology, INL/EXT-18-51329, Idaho National Laboratory
3. Charles Forsberg, Stephen Brick, and Geoffrey Haratyk, “Coupling Heat Storage to Nuclear Reactors for Variable Electricity Output with Base-Load Reactor Operation, *Electricity Journal*, **31**, 23-31, April 2018, https://doi.org/10.1016/j.tej.2018.03.008
4. The Future of Nuclear Energy in a Carbon Constrained World, Massachusetts Institute of Technology, https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf
5. C. Forsberg, K. Dawson, N. Sepulveda, and M. Corradini, *Implications of Carbon Constraints on (1) the Electricity Generating Mix for the United States, China, France and the United Kingdom and (1) Future Nuclear System Requirements*, MIT-ANP-TR-184 (March 2019)
6. Charles W. Forsberg (March 2019): Commentary: Nuclear Energy for Economic Variable Electricity: Replacing the Role of Fossil Fuels, *Nuclear Technology*, **205**, iii-iv, DOI:10.1080/00295450.2018.1523623

Take Away Messages

- Restrictions on carbon emissions and the addition of wind and solar PV change the electricity market
  - Volatile electricity prices including zero and negative priced electricity (low marginal cost wind and solar)
  - Need economic assured peak generating capacity
- Require a <u>system solution</u>: Nuclear co-generation (electricity and heat) with large-scale heat storage and assured peak electricity generating capacity
  - Buy electricity at times of low prices
  - Sell electricity at times of high prices
  - Operate power systems at full capacity
- Same storage/power system technologies for CSP

The Characteristics of Fossil Fuels Enable Separate Energy Supply Chains for Electricity, Industry and Transportation



In a Low-Carbon World, Need to Integrate Separate Energy Supply Chains to Minimize Costs

NREL Summary Descriptions

Technology	Storage Media	Receiver Outlet Temp (C)	Hot Storage Temp (C)	Cold Storage Temp (C)
CSP Parabolic Trough	Na/K nitrate "solar salt"	390	385	295
CSP Molten-Salt Tower	Na/K nitrate "solar salt"	565	565	290
Gen3 CSP Chloride Salt Tower	Mg/K/Na chloride	725	720	500
Gen3 CSP Sodium Receiver + Chloride-salt TES	Mg/K/Na chloride	750	720	500
Gen CSP Particle Tower	Sand		775	575

Added Information

Three Electricity Generating System Options for a Low-Carbon World that Meet the Three Requirements:

Electricity Generation
Energy Storage
Assured Peak Generating Capacity

Nuclear Energy with Heat Storage and Backup Furnace (Biofuels, Hydrogen, etc.)

Heat Generation to Electricity and Storage

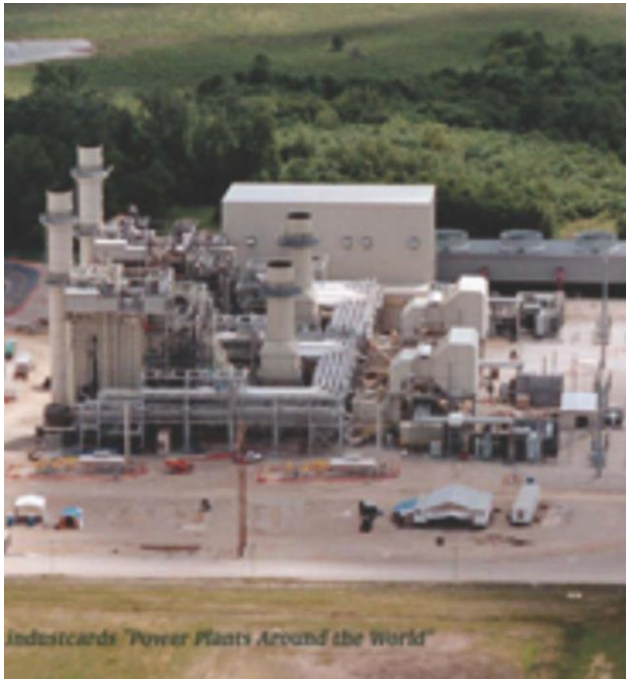
Heat Storage

Backup Boiler for Depleted Storage

Concentrated Solar Power (CSP) has Same System Design

Wind / Solar PV System With Electricity Storage and Backup Gas Turbine

McCrary Battery Storage Demonstration



Generation

Electricity Storage

Backup GT for Depleted Storage

Seasonal Solar & Wind Input Requires Significant Operation of Gas Turbine Backup (Biofuels and H_2)

Fossil Plant with Carbon Capture and Sequestration

Petra Nova (Joint venture): NGR Energy and JX Nippon Oil and Gas Exploration

- Post combustion capture CO_2
- 240 MW
  - Added to Unit 8 (654 MW)
  - 37% of Unit 8 emissions
- 90% CO_2 capture

Comparison of the Three Energy Options

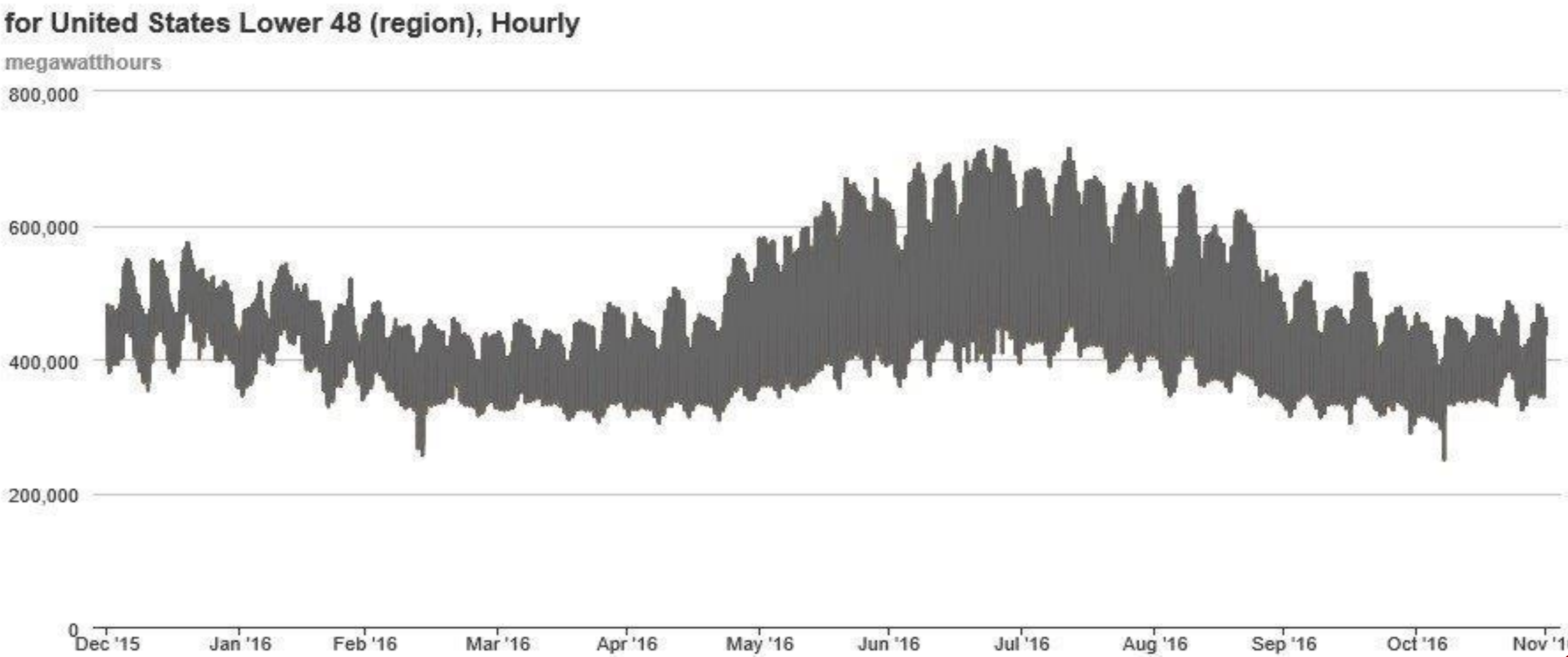
Some Mixture Likely Where Choices Depend upon Location

Option/ Characteristic	Nuclear* with Storage + Fuel	Wind/Solar PV* With Storage + Fuel	Fossil with Carbon Sequestration
1. Base-load Fuel cost	Low	~0	High
2. GW_{total}/GW_{peak}	1	>2	1
3. Low-carbon fuel (H_2, biofuels, etc.)	Low	High	None
4. Location Dependent	No	Yes	Yes

Numbered Notes below coupled to characteristics
2. GW(e) nameplate rating divided by GW(e) assured peaking capacity. Wind and solar PV total generating capacity equals Wind/Solar PV + battery + gas turbine but if extended low wind/solar conditions, the only assured capacity is the gas turbine.
3. Low-carbon fuel required for assured peaking capacity when storage is depleted. For nuclear this peaking capacity above base-load nuclear. For wind/solar this is total power because no assured base-load capability from wind and solar.
4. No location dependency for nuclear. Wind/Solar depend upon local wind and solar conditions. Fossil depend upon sequestration sites.
*Concentrated Solar Power systems have some of the characteristics of nuclear systems and some of the characteristics of solar PV

Lowest Cost System Depends upon (1) System Option Cost and (2) Best Match Between Production and Demand

- Mismatch between full production and electricity demand implies more storage and higher costs; Nuclear with storage has the closest match



Most Economic Nuclear System Depends upon Three Factors

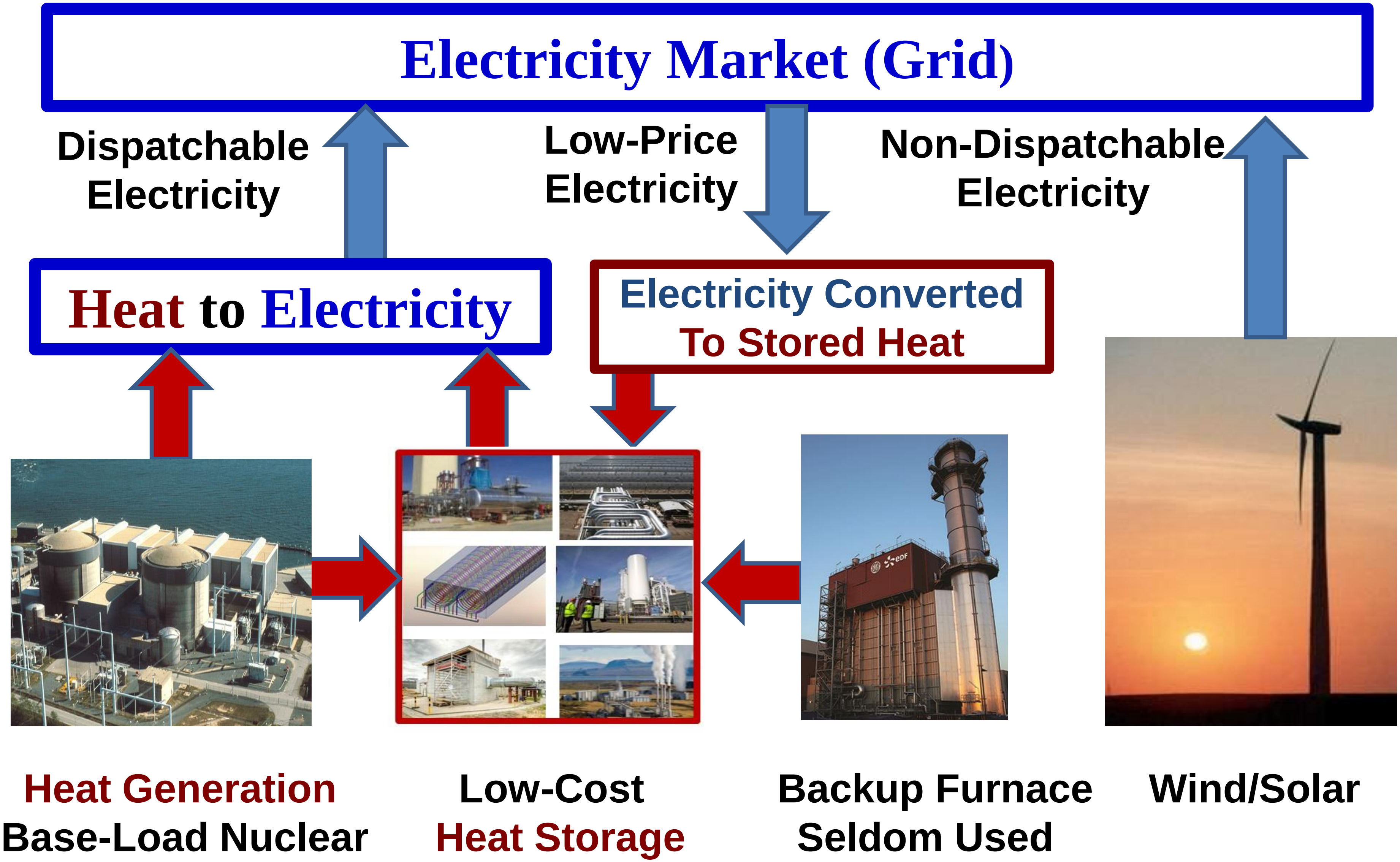
- Markets. Market with wind or solar will have different nuclear heat storage requirements because of different storage times (daily versus multiday cycles).
- Storage technology. Preferred storage technology depends upon market and reactor choice
- Reactor choice. Higher temperature reactor implies lower heat-storage costs
  - If sensible heat storage, double hot-to-cold temperature swing reduces heat storage system in half per MWh (heat)
  - Heat-to-electricity efficiency depends upon temperature. If 50% more efficient, smaller heat storage system per MWh (electricity)

Same Nuclear System for Co-Generation

Produce Variable Heat and Electricity

- Industrial heat demand twice total electricity output of the United States
  - Electricity costs 4 to 6 times the cost of heat
  - Expensive to "electrify" industry by converting electricity to heat
- Large incentives for nuclear cogeneration
  - Existing fossil cogeneration plants sometimes vary production to maximize electricity sales when prices are high. Low-cost way for nuclear co-generation added assured peak generating capacity
  - Storable manufactured fuels (hydrogen, biofuels) have massive heat and electricity inputs. Incentives to vary production with electricity prices that couples utility and transportation energy markets
- Co-generation enables optimization of combined electricity, industrial, and transportation energy markets to minimize total costs

Questions?


Electricity Market (Grid)
Dispatchable Electricity
Low-Price Electricity
Non-Dispatchable Electricity
Heat to Electricity
Electricity Converted To Stored Heat
Heat Generation Base-Load Nuclear
Low-Cost Heat Storage
Backup Furnace Seldom Used
Wind/Solar